

# DEVELOPMENT OF FOUR-CHANNEL MAGNETIC NERVE STIMULATOR

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**Abstract**—Magnetic nerve stimulators activate nervous systems by inducing electric fields inside the tissue. Due to their high power consumptions and high voltage driving requirements, only single-channel nerve stimulations have been used for clinical or research purposes. In this paper, we introduce a four-channel magnetic nerve stimulation system. The system is composed of efficient high voltage charging circuitry with small size DC power supplies and multi-channel controllers capable of driving magnetic coils with a variety of stimulation protocols. It is expected that the developed system can be used for many kinds of functional magnetic stimulations such as nerve diagnoses or magnetic acupuncture therapy.

**Keywords**—Functional magnetic stimulation, Multi-channel system, Stimulation coil, Action potential

## I. INTRODUCTION

The magnetic nerve stimulation technology was introduced in the late 1970's[1-2]. In the magnetic nerve stimulation, time varying magnetic field is used to induce electric field inside the human body. Since the electric field is induced without any physical contact to the human body, the magnetic stimulation technology is less painful while allowing depolarization of deeper nerves compared to electrical stimulation. It was reported that the rate of magnetic field change at the nerve of stimulation should be greater than several tens of Tesla/sec to stimulate the nerve tissue inside a human body. Due to the high voltage charge/discharge circuits necessary for making such a large rate of magnetic field change, stimulation frequencies of early stage magnetic stimulation systems were below several Hz. Therefore, major applications of the early stage magnetic stimulation systems were confined to diagnoses of impaired nerves with few applications to treatments. However, recent developments of high power electronics make it possible to raise the stimulation frequency up to several tens of Hz, which is comparable with that of the functional electrical stimulation (FES). As the stimulation frequency is raised up to several tens of Hz, applications of the magnetic stimulation in many kinds of functional stimulations have been increased rapidly. Recently, applications of magnetic stimulations, with the stimulation frequencies of 10 ~ 50Hz, to urinary incontinence treatments have been reported[3-4]. It is expected that functional magnetic stimulation (FMS) will replace FES to a considerable extent in the near future[5-6]. For an efficient FMS, it is essential to have multi-channel stimulation capability. In this paper, we introduce a 4-channel magnetic nerve stimulation system. We also introduce preliminary human experiment results obtained with the developed 4-channel system.

## II. METHODOLOGY

The magnetic nerve stimulator is required to produce a magnetic field of several Teslas within a short period of 1 msec to magnetically stimulate nerve or muscle tissues inside a human body. For this, a considerable amount of electrical current should be injected into a stimulation coil within the short time period. The most common way for achieving this is to charge a capacitor and discharge it instantaneously.

To develop a multi-channel magnetic stimulation system with modest size and weight, we have used the charge/discharge circuit shown in Fig. 1. In order to reduce the DC power supply output voltage, we use two discharge capacitors,  $C_{D1}$  and  $C_{D2}$ , connected in series. The discharge capacitors are connected to a stimulation coil  $L$  through a silicon controlled rectifier (SCR) and a diode,  $D$ . Between the DC power supply and the discharge capacitors, there is a charge transfer capacitor  $C_T$ . A large capacitor,  $C_P$ , is connected to the power supply to increase the output current drainage of the power supply. The charge transfer capacitor is charged by the power supply when the stimulation coil is idle. When  $SCR_1$  is ON, some of the electric energy stored at  $C_P$  are transformed to the magnetic energy at the coil  $L_1$ . When the magnetic energy of  $L_1$  reaches its maximum,  $SCR_1$  becomes OFF charging  $C_T$  up to the voltage level twice as big as that of  $C_P$ . The electric charge stored at  $C_T$  is, then, transferred to  $C_{D1}$  or  $C_{D2}$ . When  $C_{D1}$  is charged,  $SCR_{21}$  and  $SCR_{22}$  are set to ON, and for  $C_{D2}$ ,  $SCR_{23}$  and  $SCR_{24}$  are set to ON. The coil  $L_2$  is used to limit excessive current flows from  $C_T$  to  $C_{D1}$  or  $C_{D2}$ . By dividing the discharge capacitor into two parts, we can charge the discharge capacitors with a power supply of half output voltage. The reduction of power supply output voltage implies that the magnetic stimulation system can be made with reduced size and weight. The division of the discharge capacitor also makes it possible to use lower maximum repetitive peak reverse voltage ( $V_{RRM}$ ) of SCR. To further reduce the output current capacity of the power supply, we charge the discharge capacitors by multiple steps. The voltage of  $C_T$ ,  $V_{C_T}$ , is charged multiple times between the stimulation pulses. As the charge stored at  $C_T$  is transferred to the discharge capacitors, the voltage of the discharge capacitor,  $V_{C_D}$ , increases up to the desired level. When the discharge capacitors are charged up to the desired level,  $SCR_3$  is set to ON giving a sinusoidal current into the stimulation coil. The diode,  $D$ , connected with  $SCR_3$ , is for a pathway of reverse current from the stimulation coil to the discharge capacitors. Although the technique in Fig. 1 is applied to generate bi-phasic current pulses at the stimulating coil, the technique can also be applied to generate mono-phasic current pulses with minor changes of switching circuits.

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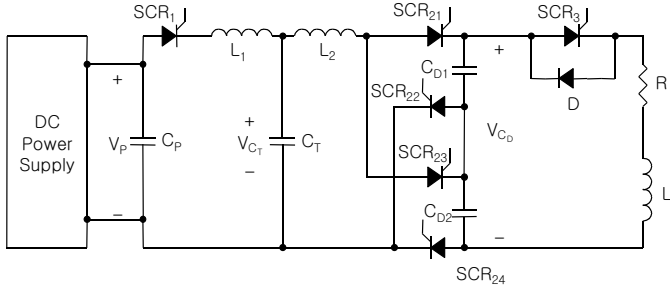


Fig. 1. The circuit for driving a stimulation coil. The stimulation coil is driven by two discharge capacitors,  $C_{D1}$  and  $C_{D2}$ , connected in series. Before the coil driving, the two discharge capacitors are charged sequentially through a charge transfer capacitor  $C_T$  and four switching devices  $SCR_{21} \sim SCR_{24}$ .

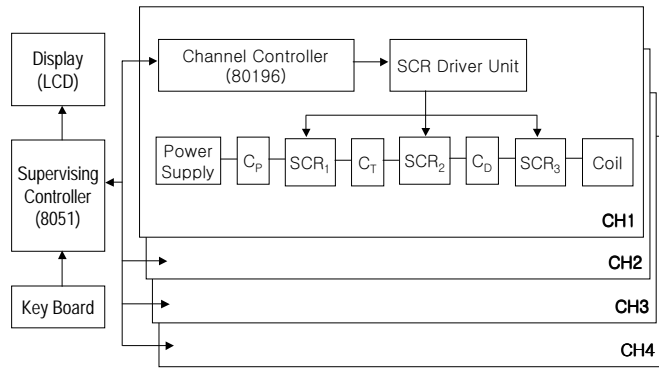


Fig. 2. A schematic block diagram of the 4-channel functional magnetic stimulation system.

Based on the charge/discharge circuit shown in Fig. 1, we have developed a 4-channel magnetic stimulation system. We show a schematic diagram of the system in Fig. 2. At each channel, a microprocessor based controller handles a sequence of power electronic device switching. The controller is made using Intel's 80196 processor. For synchronized operations of the multi-channels, a supervising controller was made using an Intel's 8051 processor. The supervising controller receives stimulation parameters, such as stimulation frequency, stimulation intensity, stimulation ON/OFF period, etc., through a keypad, and generates timing sequences for all channels. The supervising controller, then, transfers timing sequence information to each channel through serial communication links. The channel controllers interpret the timing sequence and give ready signals to the supervising controller. After the supervising controller receives ready signals, it broadcasts start signals to all channels for synchronized stimulations.

### III. RESULTS

We have developed a 4-channel magnetic nerve stimulation system and we have performed preliminary experiments on human nerves. The size and weight of the system are 50cm x 80cm x 120cm and 120kg, respectively. The DC power supply of each channel has the output voltage of 1KV and the output

current of 0.5A. Electrolyte capacitors of 2200  $\mu F$  and 1.2KV are connected to the output terminals of the power supplies. For the charge transfer capacitor  $C_T$ , we used film capacitors of 1 $\mu F$  and 2KV. For the discharge capacitors  $C_{D1}$  and  $C_{D2}$ , we used film capacitors of 100 $\mu F$  and 1KV. For nerve stimulation experiments, we used circular stimulating coils that have inner and outer diameters of 30mm and 140mm, respectively. The stimulating coils were made of copper wires that have a rectangular cross section of 2mm x 10mm. The number of turns of the coil is 26. The inductance and resistance of the coil are 40 $\mu H$  and 80m $\Omega$ , respectively. For switching elements, we used SCRs that have  $V_{RRM}$  of 2.2KV and the peak RMS ON-state current of 300A. With the choice of circuit elements, we have obtained the maximum stimulation frequency of 25Hz with the discharge voltage of 2KV. If we use lower discharge voltages, we can obtain higher stimulation frequencies. The frequency of 25Hz is believed to be quite comparable to that of conventional electrical stimulation systems.

To verify the multi-channel stimulation capability of the developed system, we have performed stimulation experiments on a healthy volunteer. Two stimulating pulses were given simultaneously to the ulnar nerves at both right and left shoulders of the volunteer. The width of the stimulating pulse was about 280 $\mu sec$ . The compound muscle action potentials (CMAPs) of abductor digiti minimi muscles were measured at both right and left palms using a homemade bio-signal measurement system. The passband and sampling frequency of the measurement system were set to 80Hz~1KHz and 5KHz, respectively. Fig. 3(a) and (b) represent the CMAPs measured at the right and left palms, respectively. The experimental results show that the developed system is capable of stimulating multiple nerves simultaneously.

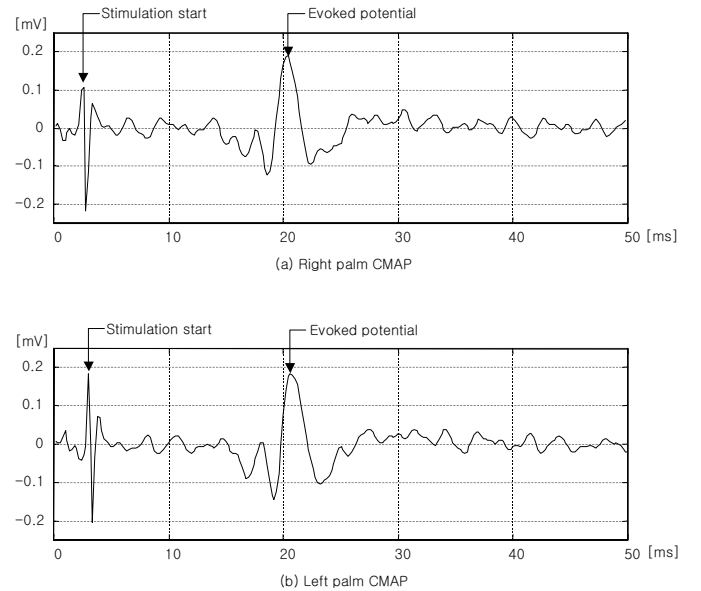


Fig. 3. CMAPs of abductor digiti minimi muscles induced by simultaneous magnetic stimulations on the ulnar nerves at the right and left shoulders of a healthy volunteer. Figures (a) and (b) represent CMAPs measured at the right and left palms, respectively.

#### IV. CONCLUSION

We have developed a 4-channel magnetic nerve stimulator capable of FMS. Using the developed system, we can stimulate four peripheral nerves simultaneously with the frequencies up to 25Hz. The developed system is believed to be suitable for preliminary experiments to figure out the possibility of FMS. Although magnetic stimulation technology has disadvantages in size, weight, and price compared with electrical stimulation technology, we think that the noninvasive stimulation capability of magnetic stimulation technology can outweigh the disadvantages in many clinical applications. It is expected that the developed system can be used for many kinds of functional magnetic stimulations such as rehabilitation of patients with neuromuscular impairments or magnetic acupuncture therapy.

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